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EVIDENCE FOR WIDESPREAD ~1760 Ma METAMORPHISM AND RAPID CRUSTAL STABILIZATION OF THE EARLY PROTEROZOIC (1870-1820 Ma) PENOKEAN OROGEN, MINNESOTA

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ABSTRACT. Regional amphibolite facies metamorphism of Early Proterozoic rocks in central Minnesota has historically been attributed solely to the 1870 to 1820 Ma Penokean collisional orogeny. New thermochronologic, thermobarometric, and geobarometric data suggest that in the internal zone of the orogen widespread staurolite-grade metamorphism occurred simultaneously with intrusion of post-Penokean (~1770-1760 Ma) plutons. We propose a P-T-t path for Early Proterozoic evolution in which Penokean-age primary garnet growth (exhibited by inclusion-rich cores) occurred during tectonic burial to pressures of 5 to 6 kb. Inclusion-free garnet overgrowths and post-kinematic staurolite formed at similar pressures but well after the orogeny and during an episode of lower crustal fusion at 1770 to 1760 Ma. Discordance between garnet rim pressures and final pluton emplacement pressures (~3.5 kb) indicates rapid uplift concomitant with magmatism and is supported by thermochronologic evidence for regional rapid cooling from above 500°C to below ~300°C at 1750 to 1760 Ma.

The proposed P-T-t path suggests that crust thickened during the Penokean orogeny remained thick for 50 to 60 my. Collapse of the overthickened orogen is characterized by sudden lower crustal melting, regional mid-crustal amphibolite facies metamorphism, and subsequent rapid uplift and cooling. Orogenic collapse appears to have been an important step in the stabilization of this part of the Proterozoic crust in the North American mid-continent. Recognition and characterization of post-Penokean metamorphism in the North American midcontinent is essential for understanding post-orogenic cratonic evolution in the Proterozoic.

INTRODUCTION

Earlier studies of the Early Proterozoic Penokean orogenic belt in central Minnesota have largely attributed metamorphic textures and structures to formation during the main compressional event at approx 1870 to 1820 Ma. In doing so the dominant tectonic features are considered to be little modified structurally since the collision. The inherent assumption is that collision and crustal thickening was followed by a period of slow erosion until the midcrustal roots of the orogenic belt were finally exposed at the surface and overlain nonconformably by 1100 Ma deposits of the mid-continent rift.

In contrast, research in the Penokean orogenic belt of northern Wisconsin and northern Michigan has led to the recognition of several post-Penokean metamorphic and deformational/uplift events, although their regional significance and their intensity is still undocumented. These include at least local recognition of post-Penokean metamorphism at ~1760 Ma in central Wisconsin (Van Wyck, ms), metamorphism at ~1720 Ma in northern Michigan (Schneider, Holm, and Lux, 1996) and central Wisconsin (Van Wyck, ms), as well as younger disturbances at ~1650 Ma (Van Schmus, Thurman, and Peterman, 1975), 1475 Ma (Van Schmus, Medaris, and Banks, 1975; Greenberg and Brown, 1983, 1985), ~1330 Ma (Peterman and others, 1985), and 1100 Ma (Peterman and Sims, 1988).

In this study we present evidence for a previously unrecognized widespread metamorphic event which affected the Precambrian rocks of central Minnesota 50 to 60 my after the close of the Penokean orogeny. Textural studies together with thermobarometry and thermochronology lead us to postulate that simultaneous lower crustal melting and midcrustal heating followed shortly by rapid exhumation and cooling represent an important event which ultimately stabilized the crust. The Penokean orogenic belt in central Minnesota provides an excellent opportunity to study Early Proterozoic stabiliza-

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tion because, unlike in Wisconsin, there has been minimal tectonic or thermal activity in this region since ~1700 Ma (Holm and Lux, 1996).

GEOLOGIC SETTING

The Early Proterozoic Penokean orogeny (1870-1820 Ma, Van Schmus, 1976, 1980) represents an island-arc (Wisconsin) and micro-continent (Minnesota)/continent collision which deformed and metamorphosed Archean and Early Proterozoic rocks of the Lake Superior region. In Minnesota, the Archean rocks affected by the collisional event consist of a northern ~2700 Ma granite-greenstone terrane and a southern Early and Middle Archean quartzofeldspathic gneiss terrane that is, in part, ~3600 Ma (Sims and others, 1980). These terranes are separated by the Great Lakes tectonic zone (GLTZ; fig. 1), a crustal scale, steeply south-dipping, ductile shear zone considered to be a late Archean (~2700-2600 Ma) crustal suture (Sims and Day, 1993). Metamorphosed ~2100 Ma mafic dikes crosscut much of the region indicating a period of Early Proterozoic extension prior to the Penokean orogeny (Sims and others, 1980). Basin sedimentation during the 2100 to 1900 Ma extensional event was followed shortly by the Penokean orogeny, and evidence for possible Early Proterozoic oceanic crust preserved near Mora, Minnesota (fig. 2; Horan, Hanson, and Spencer, 1987) suggests that the Penokean orogeny may represent the final stage of a complete Wilson cycle.

The Penokean orogenic belt in central Minnesota has been divided into three tectonic components: a northern foreland basin, a medial fold-and-thrust belt, and a southern internal zone/plutonic terrane. Sedimentary rocks of the Animikie basin, the Long Prairie basin, and the Nimrod outlier (fig. 1) have been interpreted either as foreland basin or back-arc basin sediments deposited during the Penokean collisional orogeny (Hoffman, 1988; Southwick and Morey, 1991; Hemming, McLennan, and Hanson, 1995). In the north, much of the Animikie group rocks and the underlying Mille Lacs deposits were only mildly deformed during the Penokean orogeny.

Within the medial zone, Animikie Group deposits were multiply deformed and metamorphosed during the Penokean orogeny. North-verging fold nappes are refolded into open, upright, subhorizontal east-west trending folds (Holst, 1984). Underlying these folded metasediments are numerous south-dipping, geophysically-defined thrust faults (Southwick, Morey, and McSwiggen, 1988). Metamorphic grade in the medial zone increases from greenschist facies in the north to staurolite grade of amphibolite facies just north of the McGrath Gneiss dome (Keighin, Morey, and Goldich, 1972). Thermobarometric work suggests these rocks reached maximum temperatures between 520° to 590°C and pressures of ~6 kb (Labotka, Papike, and Morey, 1981; Holm and Selverstone, 1990).

South of the Malmo Structural Discontinuity (MSD, fig. 1) the internal zone of the orogen contains both Archean high grade and Early Proterozoic medium grade metamorphic rocks intruded by syn- and post-tectonic plutons. Archean rocks are also exposed in the core of the McGrath Gneiss dome, an east-west-oriented antiformal structure (fig. 1). Geophysical studies of the poorly exposed internal zone suggest that much of that area also has similar dome-and-basin structures cored by plutonic bodies (Southwick, Morey, and McSwiggen, 1988). The McGrath Gneiss dome has been interpreted historically to have formed during Penokean compression based on its similar orientation with the upright east-west oriented folds of the medial zone (Sims and others, 1980). However, recent thermochronologic data obtained in and around the dome suggest the feature may have formed at ~1700 Ma well after the Penokean orogeny (Holm and Lux, 1996).

MAGMATIC ACTIVITY IN THE INTERNAL ZONE

Early Proterozoic syn-, late-, and post-tectonic plutons are extensive within the internal zone of the Penokean orogen (fig. 2). The interval between syn-tectonic and post-tectonic plutonism represents a change from calc-alkaline to alkaline 'anorogenic'

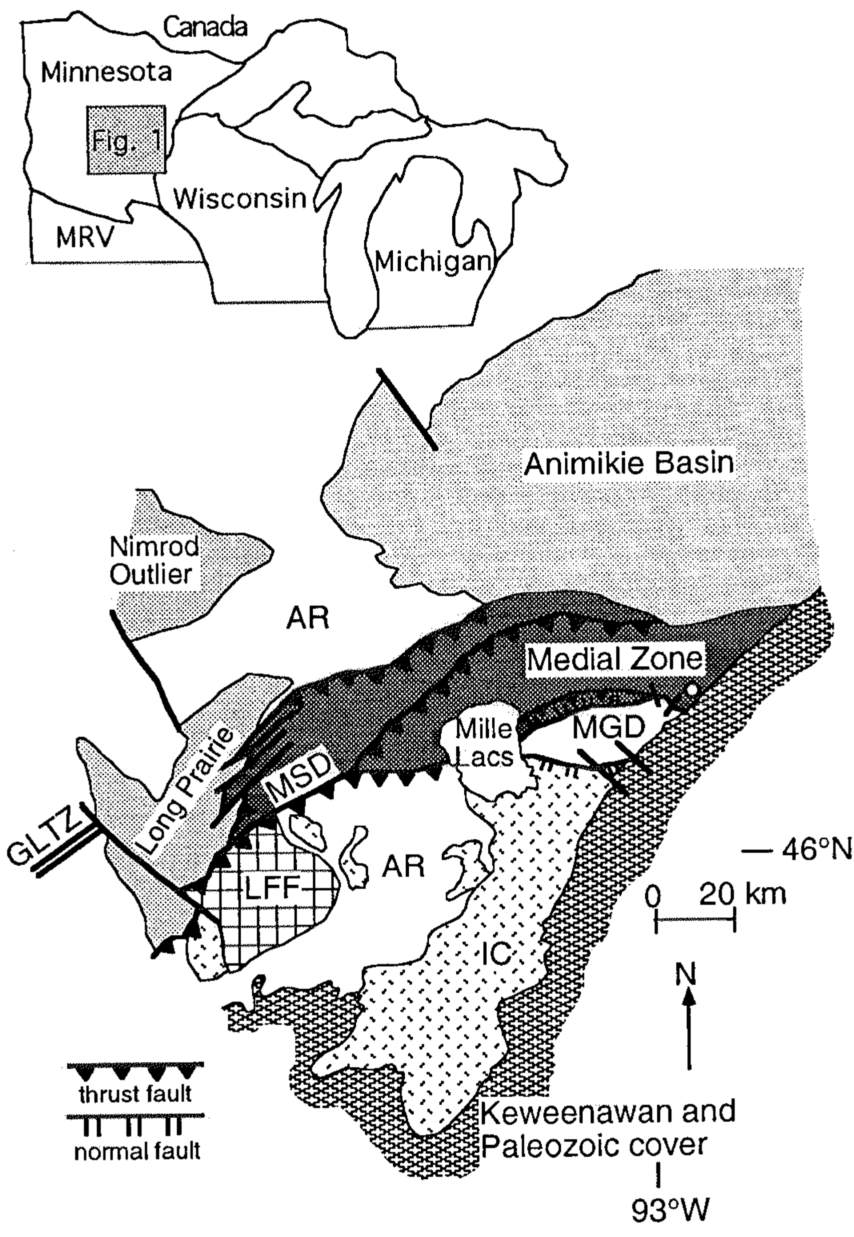

Fig. 1. Simplified map showing components of the Penokean orogenic belt (after Southwick Morey, and McSwiggen, 1988; Holm and Lux, 1996). Circle northeast of MGD denotes location of thermobarometric study by Holm and Selverstone, 1990. MSD = Malmo Structural Discontinuity; MGD = McGrath Gneiss dome; LFF = Little Falls Formation; AR = Archean rocks; IC = Early Proterozoic igneous complex of the internal zone; GLTZ = Great Lakes tectonic zone; MRV = Minnesota River Valley.

magmatism (Anderson, Cullers, and Van Schmus, 1980). Plutons traditionally considered to be syn-tectonic are the ~1870 Ma Bradbury Creek Granodiorite (Goldich and Fischer, 1986) and the undated Freedhem Granodiorite. Late-tectonic plutons include the ~1812 Ma Rockville and Reformatory Granites (Horan, Hanson, and Spencer, 1987).

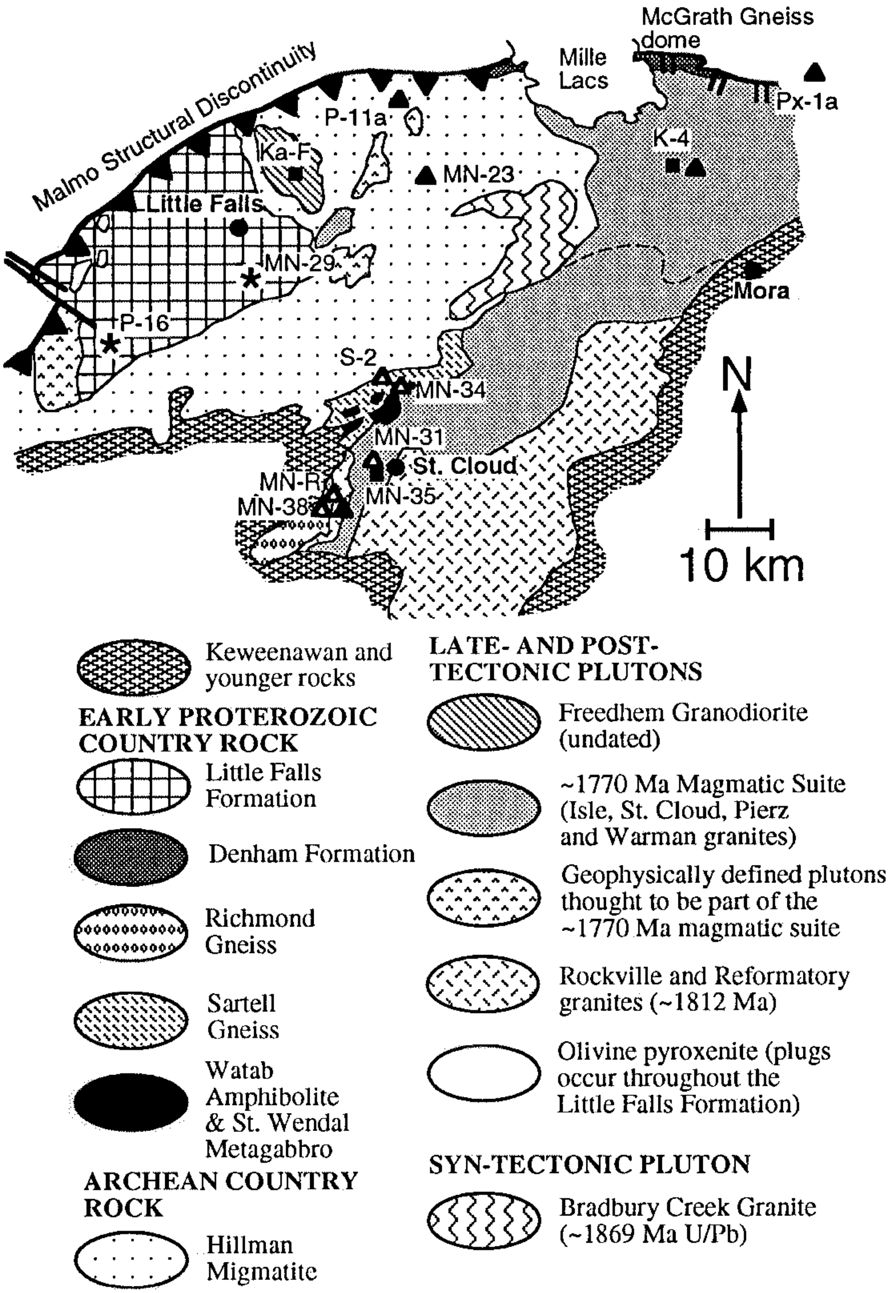

Fig. 2. Simplified map of the internal zone of the Penokean orogen in central Minnesota. Circles represent the major towns in the area, filled triangles are sample localities for hornblende $^{40}Ar/^{39}Ar$ dates, open triangles are sample localities for biotite $^{40}Ar/^{39}Ar$ dates; stars are garnet thermobarometry localities; and squares are pluton barometry localities (after Southwick, Morey, and McSwiggen, 1988; Horan, Hanson, and Spencer, 1987; Holm and Lux, 1996).

Post-tectonic plutons consist of a ~1770 to 1760 Ma magmatic suite (Spencer and Hanson, 1984) which includes the St. Cloud, Isle, Warman, and Pierz granites (similar plutons throughout Wisconsin and Michigan are often referred to as the "1760 Ma" magmatic suite). A 1741 ± 18 Ma Rb/Sr whole-rock age on the St. Cloud Granite (Goldich, 1984, reported in Horan, Hanson, and Spencer, 1987) should be considered a minimum age for the granite. Beakhouse, McNutt, and Krogh (1988) showed that Rb/Sr whole-rock dates of granites can be typically slightly younger than the crystallization age based on U-Pb results. Geochemical analyses done on similar age plutons in Wisconsin indicate that these plutons are the product of lower crustal melting (Anderson, Cullers, and Van Schmus, 1987; Nelson, 1991). Penokean and post-Penokean magmatic activity apparently extends as far south as the northern part of the Minnesota River Valley (fig. 1) where two separate intrusions give approximate ages of 1850 and 1750 Ma (Goldich and others, 1970).

Finally, rocks of central Minnesota and the northern Minnesota River Valley are commonly crosscut by several ages of mafic dikes. In the Minnesota River Valley, tholeiitic diabase dikes yield K-Ar ages of ~2080 Ma, and northeast-striking andesite dikes yield K-Ar ages between 1700 and 1800 Ma (Hanson and Himmelberg, 1967). In the St. Cloud area late basaltic dikes oriented generally northeast-southwest crosscut the post-tectonic ~1770 Ma magmatic suite and yield significantly younger K-Ar ages of 1570 to 1280 Ma (Hanson, 1968). However, these dikes have Pb isotope data consistent with an age of 1800 Ma, suggesting they were intruded shortly after the crystallization of the granites and were later reset (Horan, Hanson, and Spencer, 1987; Van Wyck, ms).

PETROLOGY AND THERMOBAROMETRY

The metamorphosed Early Proterozoic Little Falls Formation is located within the internal zone of the Penokean orogenic belt (fig. 2). It is a biotite-quartz-plagioclase-muscovite schist whose protolith was a shale and graywacke sequence with carbonate concretions (Southwick, Morey, and McSwiggen, 1988). Within the unit metamorphic grade increases from garnet grade in the north to staurolite grade in the south. Goldich and others (1961) suggested that the Little Falls Formation and the pelitic schist studied by Holm and Selverstone (1990) located ~150 km to the northeast were part of the same unit based on similarities of composition and metamorphism.

Two samples of the Little Falls Formation were collected from within the staurolite zone. Sample MN-29 is from below the Blanchard Dam south of Little Falls, and sample P-16 is a drill core sample provided by the Minnesota Department of Natural Resources (fig. 2). The garnets from both samples are about 1 to 2 mm in diameter and are characterized by quartz-inclusion-rich cores and inclusion-free rims (fig. 3A) suggesting two stages of garnet growth (see also Holm and Selverstone, 1990). In east-central Minnesota the inclusion-rich cores exhibit spectacular spiral inclusion trails indicating synkinematic growth (see photomicrographs published in Holm, Holst, and Ellis, 1988, and in Holm and Selverstone, 1990). The garnets occur both within the matrix and as inclusions within 1 to 2 cm staurolite porphyroblasts (fig. 3B). Staurolite crosscuts the main fabric of the unit and is considered to be post-kinematic (see also Holm, Holst, and Ellis, 1988, fig. 3B).

Compositional zoning trends were obtained from two garnets for each sample from the staurolite zone. Chemical analyses were obtained using a Cameca SX50 electron microprobe at the Department of Geological Sciences, Indiana University, Bloomington. The compositional data from all four garnet traverses yielded similar profiles (fig. 4;

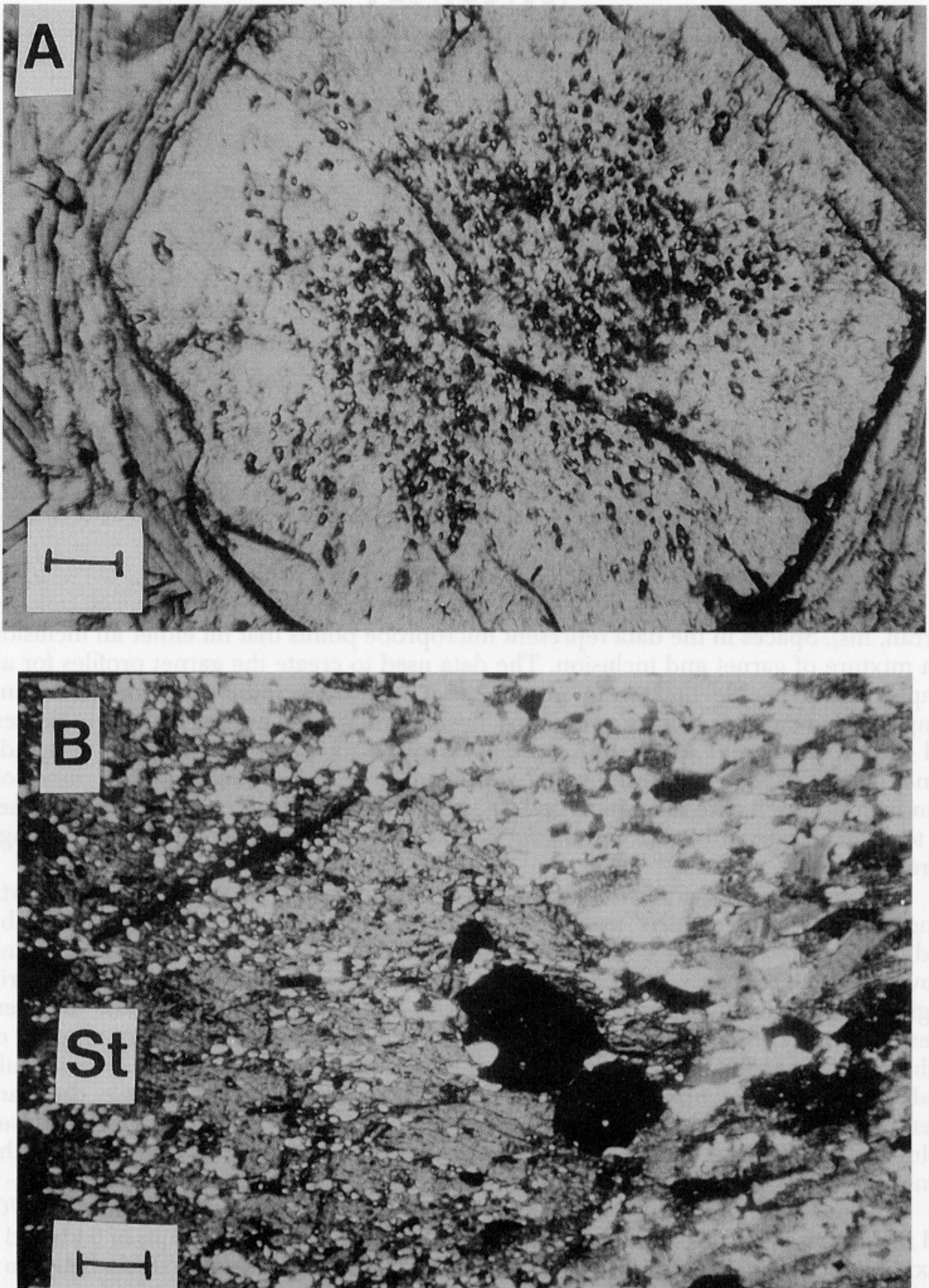

Fig. 3(A) plane-light photomicrograph of garnet P-16-1 and adjacent biotite from drill core sample of the Early Proterozoic Little Falls Formation. Note inclusion rich core and relatively inclusion free rims. Scale bar is 120 microns. (B) cross-nicols photomicrograph of staurolite porphyroblast (St) with garnet inclusions (center), some of which show inclusion-rich cores and inclusion-free rims (sample MN-29). Right side of photomicrograph shows quartz-feldspar-biotite matrix. Scale bar is 500 microns.

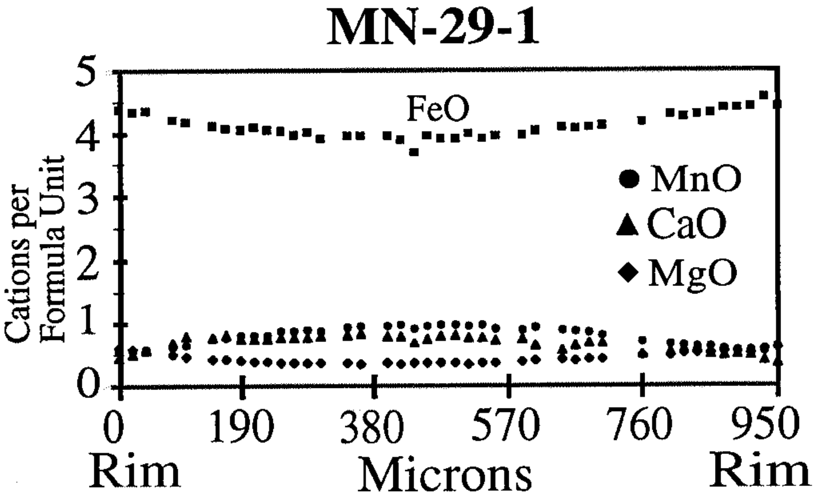

Fig. 4. Compositional zoning profile for garnet from sample MN-29-1 of the Early Proterozoic Little Falls Formation. Spaces in the data represent microprobe points that either hit inclusions or mixture of inclusion with garnet.

Darrah, ms). Spaces in the data represent microprobe points that hit either an inclusion or a mixture of garnet and inclusion. The data used to create the garnet profiles for all samples are available in Darrah (ms). Garnet interiors exhibit uniform almandine compositional patterns. Closer to the rims, the almandine and pyrope content increases, and the grossular and spessartine content decreases, a trend that suggests prograde garnet growth. These compositional changes appear to correspond with the transition from inclusion-rich core to an inclusion-free rim when present. However, in some cases the textural change within the garnets appears abrupt whereas the compositional change is gradational.

We obtained temperature and pressure estimates of garnet core and rim growth using the thermobarometric techniques of Ferry and Spear (1978) as modified by Hodges and Spear (1982) and Ghent and Stout (1981) as modified by Hodges and Crowley (1985). Because only quartz occurs as inclusions within the garnets, matrix plagioclase, biotite, and muscovite compositions were employed to estimate the pressures of garnet core growth. The samples we studied contain an abundant amount of both muscovite and biotite compared to garnet, and the matrix plagioclase grains, while small, show no evidence of zonation. Our samples lack the appropriate divariant assemblage necessary to model P-T paths of garnet growth using the Gibbs Method (see Holm and Selverstone, 1990). Microprobe analyses were done on garnets used for the garnet profiles as well as on an additional garnet from each sample (see app. A).

Core analyses for sample MN-29 gave temperature estimates of a minimum of 470° and maximum of 520°C. Garnet core pressure estimates gave a minimum of 5 kb and a maximum of 6 kb (fig. 5A). Rim analyses yielded slightly higher temperatures between a minimum of 500° and a maximum of 570°C. Garnet rim pressures were similar to those obtained from the garnet cores with a minimum estimate of 4.5 and a maximum of 6.3 kb (fig. 5B). The same calculations were repeated on sample P-16. Garnet core temperature estimates were between 440° and 475°C. Pressure estimates for garnet core growth were between 5 and 6 kb (fig. 5C). The rims record slightly higher temperatures between 470° and 520°C with pressures between 4.5 and 6 kb (fig. 5D). The results of the thermobarometry calculations suggest that garnets grew during heating under relatively isobaric

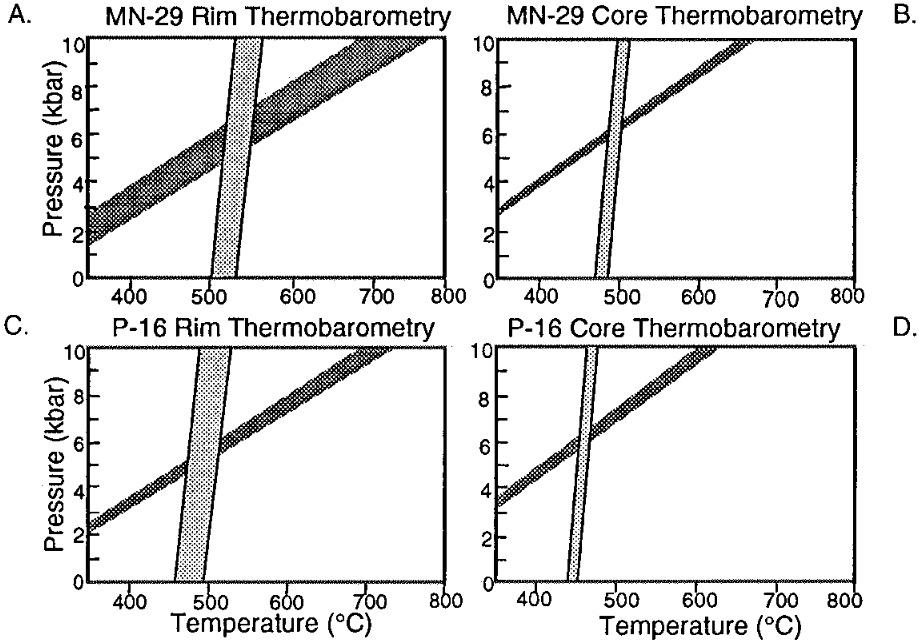

Fig. 5. Pressures and temperatures of garnet rim (A and C) and core (B and D) equilibration of the Little Falls Formation, central Minnesota. Screened areas show ranges of K_D lines calculated using biotite-garnet thermometry (Ferry and Spear, 1978; Hodges and Spear, 1982) and plagioclase-garnet-muscovite-biotite barometry (Ghent and Stout, 1981; Hodges and Crowley, 1985).

conditions. The temperature estimates for MN-29 were generally higher than those for P-16. However, the relative amount of temperature increase from core to rim for the two samples is about equal. The P-T results concur with previous work done in other areas of the orogenic belt (Labotka, Papike, and Morey, 1981; Dacre, Himmelberg, and Morey, 1984; Holm and Selverstone, 1990).

RESULTS OF ^{40}AR/^{39}AR THERMOCHRONOLOGY

Sample preparation, irradiation, and analytical procedures for $^{40}Ar/^{39}Ar$ incremental release dating follow the procedures described by Lux (1986). Samples were encapsulated in tin foil and irradiated in the L67 facility of the Ford Nuclear Reactor, Phoenix Memorial Laboratory at the University of Michigan. Variations in neutron flux during irradiation were monitored with a biotite mineral standard (University of Maine laboratory standard, SBG-7: 240.9 Ma). The samples were heated in a molybdenum crucible within an ultrahigh vacuum system, on line to a Nuclide model 6-60-SGA mass spectrometer, using radio frequency induction and were collected digitally. Samples were analyzed by the incremental heating technique in which the sample is heated repeatedly at successively higher temperatures. Results are presented as release spectra in which the horizontal width of each box represents the size of an increment relative to the others, and the height represents the uncertainty associated with each apparent age. Plateau ages (designated as Tp) were calculated from consecutive gas increments that together constitute >50 percent of the total gas released. Uncertainties are reported at the 2σ level and include the uncertainty in the flux measurement (J value). No argon diffusivity data were obtained for the minerals analyzed, and typical closure temperatures (T_c) of 500° ± 50°C for hornblende and 300°C for biotite are assumed (McDougall and Harrison, 1988).

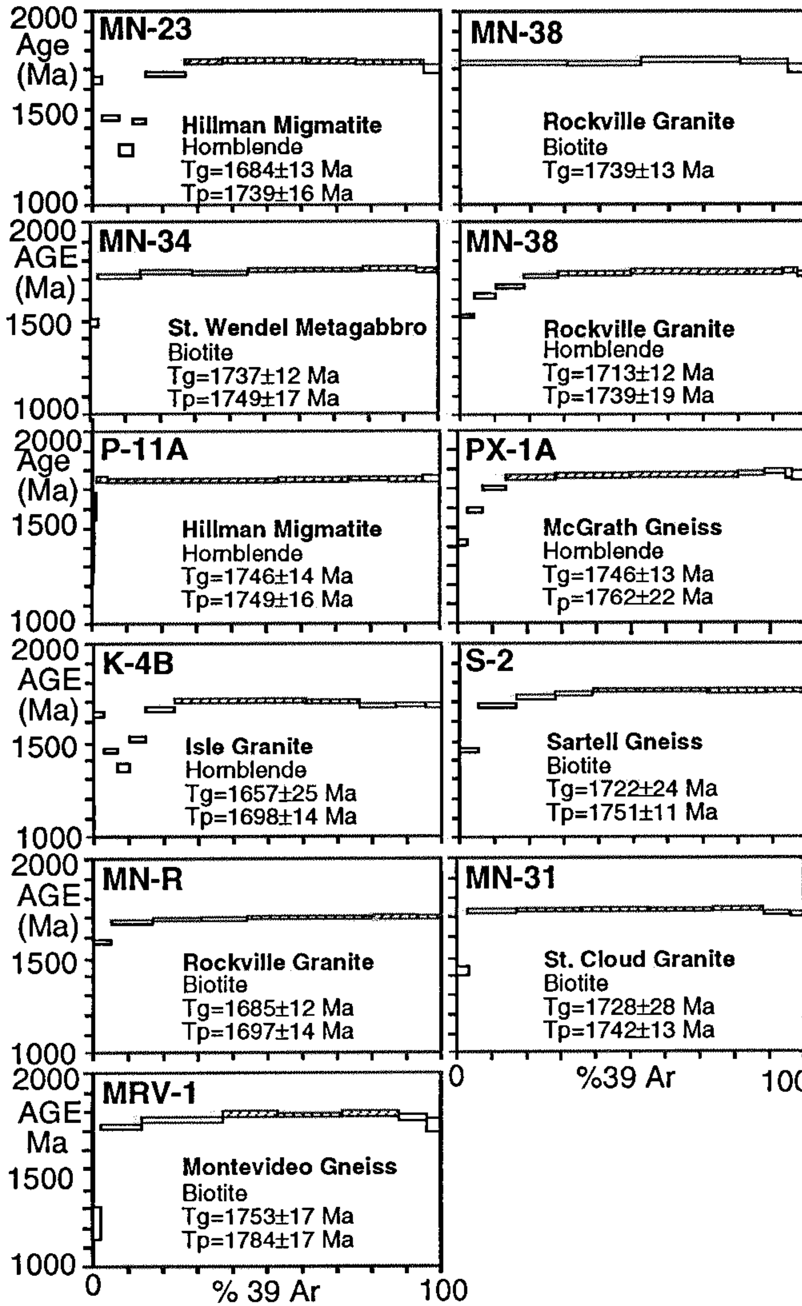

Fig. 6. $^{40}Ar/^{39}Ar$ release spectra diagrams. Tg, total gas date; Tp, plateau date.

Hornblende thermochronology.–Five samples of hornblende were prepared and dated using the $^{40}Ar/^{39}Ar$ technique (fig. 6 and app. B). The sample localities are shown on figure 2, and thin section descriptions are available in Darrah (ms). Ten to eleven heating increments were performed on the hornblende separates, all of which gave plateau dates. Sample PX-1A was obtained from a drill core sample of the Archean McGrath Gneiss. The hornblende separate yielded a total gas age of 1746 ± 13 Ma and a plateau age of 1762 ± 22 Ma. Two samples were obtained of the Hillman Migmatite, one of which is a drill core sample (P-11A) provided by the Minnesota Department of Natural Resources. Sample P-11A yielded a total gas age of 1746 ± 14 Ma and a concordant plateau age of 1749 ± 16 Ma. The second Hillman Migmatite sample (MN-23) gave a slightly younger plateau age of 1739 ± 16 Ma. The 1684 ± 13 Ma total gas age from this sample reflects disturbance in the first 25 percent of the gas released. Two hornblende separates were obtained from plutonic rocks in central Minnesota. Sample MN-38 from the 1812 Ma Rockville Granite yielded a total gas age of 1713 ± 12 M and a plateau date of 1739 ± 19 Ma. Drill core sample K-4b from the ~1770 Ma Isle Granite yielded an anomalously young total gas age of 1657 ± 25 Ma and plateau age of 1698 ± 14 Ma.

Biotite thermochronology.–Holm and Lux (1996) obtained nine $^{40}Ar/^{39}Ar$ biotite dates from Precambrian bedrock south of the Malmo Structural Discontinuity and north of the St. Cloud area (fig. 2). Six new $^{40}Ar/^{39}Ar$ biotite dates were obtained in this study: five from the region surrounding St. Cloud (fig. 2), and one from the Minnesota River Valley (fig. 1). The new dates from central Minnesota are similar to results obtained by Holm and Lux (1996). Samples of the Early Proterozoic St. Wendel Metagabbro (sample MN-34) and Sartell Gneiss each yielded concordant plateau ages of 1749 ± 17 and 1751 ± 11 Ma, respectively. Biotite from the 1770 Ma St. Cloud Granite (sample MN-31) yielded a slightly younger plateau age of 1742 ± 13 Ma. Two biotite dates were obtained from the ~1812 Ma Rockville Granite. Biotite from sample MN-38 yielded a plateau date of 1739 ± 13 Ma exactly concordant with the hornblende date from the same sample reported above. However, biotite from sample MN-R yielded a younger plateau date of 1697 ± 14 Ma.

A sample of the Archean Montevideo gneiss from its type locality in the Minnesota River Valley yielded a biotite plateau date of 1784 ± 17 Ma (fig. 6). This is the first $^{40}Ar/^{39}Ar$ date obtained from the Minnesota River Valley and is comparable to K-Ar dates obtained decades ago by Goldich and others (1961) for samples north of the Yellow Medicine Shear Zone (Southwich and Chandler, 1996). It is noteworthy that this particular date, obtained south of the internal zone of the Penokean orogen, is older than any of the 30 or so biotite, muscovite, or hornblende Ar/Ar dates obtained thus far from the internal zone of the orogenic belt (Holm, Holst, and Lux, 1993; Holm and Lux, 1996; this study).

Discussion of thermochronologic results.–With the exception of hornblende from the drill core of Isle Granite, all the hornblende separates from central Minnesota yield relatively uniform dates around 1750 to 1760 Ma. An additional hornblende sample from an earlier study of the Early Proterozoic Denham Formation (north of the McGrath Gneiss dome) also gave a cooling age of 1756 ± 16 Ma (Holm, Holst, and Lux, 1993). Biotite from the same Isle Granite drill core dated here yielded a cooling age of 1756 ± 16 Ma, similar to the other biotite ages in the region (Holm and Lux, 1996) and 50 my older than the higher-temperature hornblende date. It is very unlikely that the 1756 Ma biotite date represents excess argon given the remarkable uniformity of biotite, and even hornblende, dates throughout the area. For this reason the hornblende date from the ~1770 Ma Isle Granite is interpreted as geologically meaningless.

Except for one 1700 Ma biotite date from the Rockville Granite (sample MN-R), all the biotite dates from central Minnesota are concordant within error with the 1750 to 1760 Ma hornblende dates. In an earlier study Holm and Lux (1996) argued that uniformity of ~1755 Ma biotite $^{40}Ar/^{39}Ar$ dates in east-central Minnesota indicated rapid cooling. The new thermochronologic data reported are consistent with that interpretation and suggest the region cooled quickly after intrusion of the post-tectonic plutons. The one 1700 Ma biotite date is the same as mica Ar/Ar cooling dates obtained previously solely within the McGrath Gneiss dome (Holm and Lux, 1996). Although mica dates right nearby (that is, samples MN-38 and MN-31) are substantially older, this new date does indicate that some localized thermal resetting of country rock outside the gneiss dome did occur during gneiss dome formation.

RESULTS OF PLUTON BAROMETRY

Archean and Early Proterozoic metamorphic rocks in central Minnesota record relatively uniform paleopressures of 5 to 6 kb associated with the Penokean collisional orogeny (Labotka, Papike, and Morey, 1981; Dacre, Himmelberg, and Morey, 1984; Holm and Selverstone, 1990; this study). In order to assess the post-collisional exhumation history of this part of the orogen, the empirical Al-in-hornblende (AH) igneous barometer developed by Hammarstrom and Zen (1986) was utilized to estimate emplacement depths of the post-tectonic magmatic units. Both field and experimental studies have shown that, in the presence of the appropriate buffer assemblage, the total Al content of hornblende rims is a sensitive linear function of crystallization pressure. In order to use the AH barometer the plutonic rocks must contain plagioclase, hornblende, biotite, potassium feldspar, quartz, titanite, magnetite, or ilmenite, ± epidote. The field-based calibrations of the barometer by Hammarstrom and Zen (1986) and Hollister and others (1987) are virtually identical to the experimental calibration by Schmidt (1992). In contrast, the experimental calibration by Johnson and Rutherford (1989) yields pressure significantly lower for a given hornblende Al content. The Johnson and Rutherford (1989) calibration was accomplished at temperatures ~100°C higher than solidi for typical granitic magmas with $P_{tot} = P_{CO2} + P_{H2O}$, whereas the Schmidt (1992) calibration was carried out under more typical water saturated magmatic conditions at temperatures of 700° to 655°C.

Six different plutonic bodies were sampled within the internal zone of the orogenic belt in central Minnesota from 10 different localities. The localities, rock types, and thin section descriptions for these samples can be found in Darrah (ms). Of the ten localities sampled, four contained the appropriate mineral assemblage required for the barometer. Of these four, three yield uniform aluminum content from hornblende rim microprobe analyses. The results of microprobe analyses of the undated, moderately deformed Freedhem Granodiorite (sample KA-F) and the ~1770 Ma Isle (sample K-4) and St. Cloud (sample MN-35) Granites are recorded in table 1. Microprobe analyses on the hornblendes were performed at Indiana University, Bloomington. The localities of these samples within the internal zone of the orogenic belt are shown on figure 2.

Pressure was calculated for each microprobe point and then averaged to give a mean estimate of depth of intrusion for each sample. A comparison of the results of the application of the AH barometer to these three samples is summarized in table 2. Because the hornblendes are all fairly Mg-rich, the anomalous pressure estimates from Fe-rich amphiboles recognized by Ague and Brimhall (1988) are not a problem. The Schmidt (1992) calibration of the AH barometer probably gives the best estimate of depth of intrusion for these plutons. Pressures obtained by the Johnson and Rutherford calibration give depth of intrusion estimates that seem unreasonably low (8.5 km for the Freedhem Granodiorite and 9.1 km for the Isle Granite, assuming a crustal density of 2.7 g/cc). Biotite from both post-tectonic plutons and from the metasedimentary country rock throughout the internal zone yield uniform $^{40}Ar/^{39}Ar$ cooling ages between 1750 to 1760 Ma indicating that the intrusions were emplaced into country rock with ambient temperatures above 300°C (Holm and Lux, 1996). Considering an upper-crustal geother-

TABLE 1

Cation proportions (per 23 oxygens) from rim analyses of hornblende in the Freedhem Granodiorite (KA-F), the Isle Granite (K-4), and the St. Cloud Granite (MN-35)

Sample	Si	Ti	Al	Mg	Ca	Mn	Fe	Na	K
KA-F-1	6.89	0.15	1.34	2.72	1.90	0.08	1.98	0.32	0.18
	6.92	0.14	1.33	2.71	1.88	0.07	1.98	0.36	0.16
	6.76	0.14	1.51	2.51	1.97	0.07	2.17	0.25	0.17
	6.84	0.15	1.42	2.60	1.95	0.07	2.02	0.32	0.18
KA-F-2	6.85	0.13	1.36	2.79	1.95	0.07	1.96	0.33	0.17
	6.82	0.15	1.44	2.64	1.92	0.07	2.00	0.36	0.18
	6.85	0.16	1.34	2.72	1.92	0.07	2.00	0.38	0.17
	6.83	0.16	1.40	2.71	1.88	0.07	1.99	0.36	0.19
	6.82	0.14	1.45	2.66	1.89	0.09	1.97	0.39	0.19
K-4-1	6.85	0.11	1.38	2.55	1.92	0.09	2.17	0.37	0.17
	6.81	0.12	1.47	2.49	1.94	0.08	2.16	0.38	0.17
	6.86	0.12	1.41	2.52	1.97	0.08	2.12	0.35	0.16
	6.93	0.08	1.36	2.64	1.90	0.08	2.07	0.35	0.15
	6.89	0.10	1.39	2.54	1.92	0.09	2.13	0.31	0.16
K-4-2	6.94	0.10	1.32	2.57	1.93	0.08	2.11	0.35	0.15
	7.01	0.09	1.29	2.59	1.94	0.07	2.03	0.34	0.15
	6.99	0.09	1.28	2.63	1.92	0.08	2.04	0.36	0.14
K-4-3	6.96	0.09	1.31	2.57	1.90	0.09	2.12	0.37	0.15
	6.97	0.07	1.32	2.64	1.99	0.09	2.06	0.32	0.14
	6.83	0.11	1.45	2.53	1.93	0.09	2.12	0.39	0.16
MN-35-1	6.59	0.22	1.64	0.24	1.87	0.05	4.42	0.39	0.27
	6.55	0.22	1.64	0.25	1.84	0.06	4.46	0.51	0.28
	6.58	0.21	1.63	0.22	1.85	0.06	4.50	0.43	0.27
MN-35-2	6.71	0.16	1.54	0.21	1.88	0.07	4.47	0.36	0.26
	6.74	0.14	1.53	0.23	1.89	0.06	4.45	0.39	0.26
	6.64	0.16	1.63	0.22	1.89	0.05	4.49	0.35	0.26
MN-35-3	6.59	0.18	1.63	0.21	1.78	0.08	4.50	0.60	0.27
	6.61	0.21	1.64	0.25	1.80	0.07	4.38	0.58	0.25

TABLE 2

Average emplacement pressures (kb) of post-Penokean plutons. HZ represents Hammarstrom and Zen (1986), JR represents Johnson and Rutherford (1989), and S represents Schmidt (1992) calibrations

Rock Unit	Sample	Age	HZ	JR	S
St. Cloud	MN-35	1770 Ma	4.1 ± 3	3.3 ± 0.5	4.6 ± 0.6
Freedham	KA-F	undated	3.1 ± 3	2.5 ± 0.5	3.6 ± 0.6
Isle	K-4	1770 Ma	2.9 ± 3	2.3 ± 0.5	3.5 ± 0.6

mal gradient in the range of 20° to 30°C/km, this suggests a minimum depth estimate of 10 to 15 km for emplacement of these plutons.

Using the calibration of Schmidt (1992), the St. Cloud Granite intruded at a pressure of 4.6 ± 0.6 kb. Assuming an average overburden density of 2.7 g/cc, this corresponds to a depth of ~17 ± 2 km. However, the comagmatic Isle Granite intruded at a pressure of 3.47 ± 0.6 kb corresponding to a depth of 13 ± 2 km. The fact that different intrusions of the ~1770 Ma magmatic suite yield different emplacement pressures suggests that crystallization occurred simultaneously with post-orogenic uplift. Although it has not been dated, the Freedhem Granodiorite has been commonly considered a syntectonic pluton associated with the Penokean collisional orogeny, because it commonly exhibits foliation and cross-cutting shear zones. However, its shallower depth of emplacement (~13.5 km) relative to the post-tectonic St. Cloud Granite suggests that it could be post-tectonic. Deformation features in the Freedhem Granodiorite and the country rock structural domes mentioned above may well be features formed during exhumation of the Penokean orogen.

LATE MAFIC DIKES AND BRITTLE SHEARS

The late- and post-tectonic magmatic suites of central Minnesota are extensively crosscut by steeply dipping to vertical brittle shear zones and mafic dikes that generally trend northeast-southwest to east-west. Much of the region affected by the Penokean orogeny, including central Minnesota, Wisconsin, and the upper peninsula of Michigan, is crosscut by similar late northeast-trending mafic dikes (King, 1990). Some of these dikes are certainly related to 1100 Ma mid-continent rift magmatism (Green and others, 1987; Holm and Lux, 1997). However, some are also significantly older and appear related to the ~1770 to 1760 Ma magmatic suite. For instance, in Wisconsin, northeast-oriented mafic dikes that crosscut ~1770 Ma plutons were metamorphosed to amphibolite facies at ~1720 Ma (Van Wyck, ms). In addition, in central Minnesota Pb isotope data from some mafic dikes in the St. Cloud area are consistent with a ~1800 Ma age suggesting that the dikes may have intruded only shortly after emplacement of the ~1770 to 1760 Ma magmatic suite (Horan, Hanson, and Spencer, 1987).

Figure 7 is a composite stereonet plot showing the general steep dip and east-northeast orientation of brittle shear zones from four separate localities near St. Cloud. Individually most of the shear zones are about 2 to 4 cm thick, but they do tend to cluster and produce shear "bands" of up to 0.3 m width. Outcrop relations suggest that at least some of the northeast striking dikes used the shear zones as conduits, because the dikes tend to follow the shears and shear splays. The brittle shears tend to be much more numerous in the vicinity of the mafic dikes than away from the dikes.

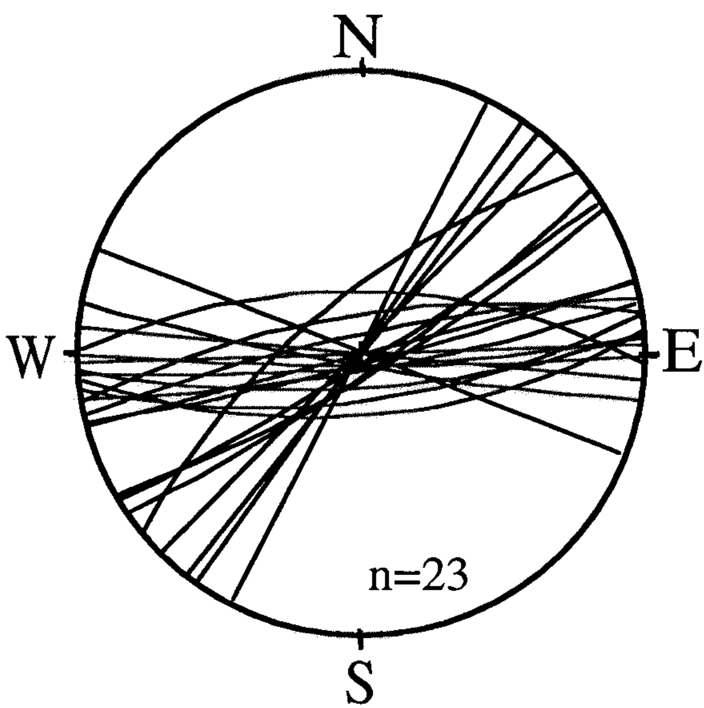

Fig. 7. Stereonet plot of brittle shears which cross-cut 1770 Ma plutonic rocks.

Thin sections were cut of a representative shear zone from the ~1770 Ma St. Cloud Granite. The grains in and around the brittle shear exhibit semi-ductile features such as undulose extinction, subgrain development, and recrystallization. These same grains are cut by brittle fractures and have experienced brittle grain size reduction. These observations qualitatively suggest that the temperature of these rocks was probably somewhat elevated (near ~300°C) during initial formation of the shear zones. The brittle shears are crosscut by late mafic dikes of probable Early Proterozoic age indicating that they formed very shortly after emplacement of the plutons. As noted above, the plutons were intruded during a period of rapid crustal exhumation, and we suggest that the shear zones manifest continued uplift and deformation during cooling after emplacement.

POST-PENOKEAN METAMORPHISM AND RAPID EXHUMATION

Figure 8 is a proposed pressure-temperature-time path of the evolution of the internal zone rocks beginning with tectonic burial of the Little Falls Formation to pressures of 5 to 6 kb as indicated by garnet core thermobarometry. The inclusion-rich garnet cores are interpreted to represent synkinematic mineral growth during the Penokean orogeny. Although no timing constraints were provided, Holm, Holst, and Ellis (1988) proposed that garnet cores and rims and late staurolite porphyroblasts all formed during a single progressive metamorphic event. In that scenario, the garnet-rim metamorphic conditions were interpreted to be associated with conductive relaxation after crustal thickening during the orogeny. However, it seems unlikely that the 1760 to 1750 Ma hornblende dates obtained here would represent initial cooling below ~500°C after being metamorphosed over 50 my earlier during the Penokean orogeny. Time-scales for thermal relaxation after crustal thickening in Phanerozoic orogens are much

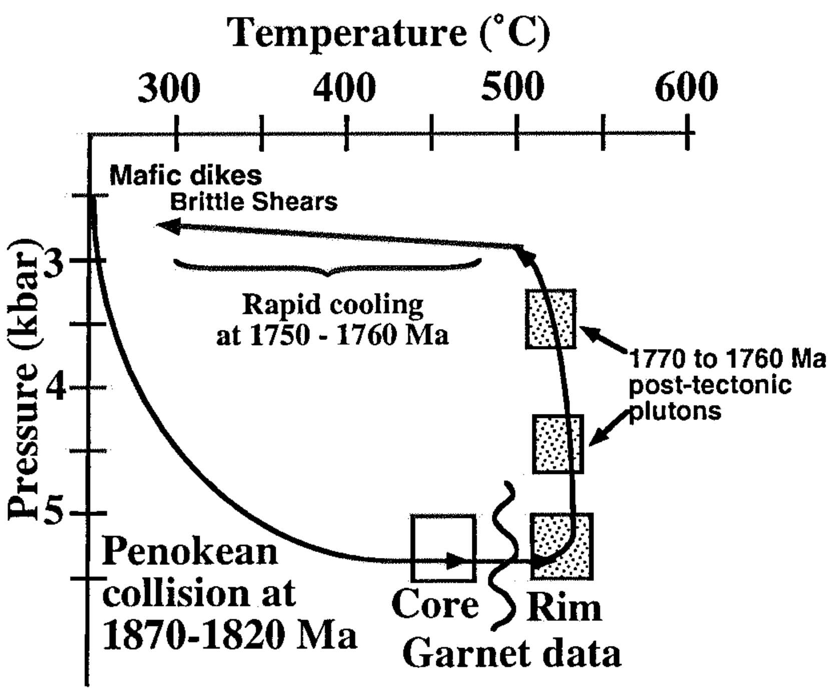

Fig. 8. Summary P-T-t path for Early Proterozoic sediments of the internal zone of the Penokean orogen. Stippled boxes are interpreted as representing post-orogenic essentially concomitant metamorphism (garnet rim and staurolite growth) and rapid unroofing.

shorter than 50 my. In addition, the petrography of the metamorphosed Early Proterozoic sediments summarized above and in Holm and Selverstone (1990) suggests these rocks underwent a second metamorphic event which reached staurolite grade. The results of $^{40}Ar/^{39}Ar$ dating of hornblende suggest to us that amphibolite facies metamorphism last occurred simultaneously with generation and upward advection of the ~1770 to 1760 Ma magmatic suite. In essence, we propose that the rocks of the internal zone were widely remetamorphosed to staurolite grade during the same event which caused abrupt orogen-wide lower crustal melting at 1770 to 1760 Ma. If so, then the garnet rim metamorphism would yield pressure and temperature conditions well after the Penokean orogeny (fig. 8).

Our proposed scenario for a widespread post-Penokean metamorphic event is supported by a recently determined model U/Pb age on staurolite in the Little Falls Formation (Lanzirotti and Hanson, 1993; A. Lanzirotti, personal communication, 1996). In their 1993 abstract Lanzirotti and Hanson reported a ~1712 Ma staurolite date which was based on an assumed initial Pb ratio. Since then, Lanzirotti has analyzed the whole rock from which the staurolite was separated and obtained a recalculated 'model' age of ~1751 Ma which is within error of the crystallization age of the post-tectonic plutons (A. Lanzirotti, personal communication, 1996). The $^{40}Ar/^{39}Ar$ hornblende data presented here, together with this independently obtained 'model' U/Pb staurolite date, strongly suggest that the pressures and temperatures recorded by the garnet rims represent metamorphic conditions well after the Penokean orogeny.

The growth of the late garnet rims and staurolite occurred while the ~1770 to 1760 granites were advecting through the midcrust. The pressure estimates from final garnet equilibration are ~5 to 6 kb, yet pressures of final emplacement of the plutons are ~4.5 to 3.5 kb. The discordance between the pressure estimates suggests that the region underwent rapid exhumation very shortly after the lower crust began melting to form the post-tectonic plutons. Following intrusion and rapid uplift the entire region then cooled rapidly through ~500° and 300°C between ~1760 and ~1750 Ma as indicated by the concordant $^{40}Ar/^{39}Ar$ hornblende and biotite cooling dates (fig. 8; see also Holm and Lux, 1996).

IMPLICATIONS FOR CRUSTAL STABILIZATION

We have presented data in this paper that suggest that the Early Proterozoic sediments in central Minnesota were metamorphosed twice: initially during the Penokean orogeny and again during an episode of post-orogenic magmatism at 1770 to 1760 Ma. We do not envision the younger metamorphism as simply reflecting local contact metamorphism adjacent to mid- or shallow crustal plutons. The lack of any Penokean-age hornblende dates and the relatively uniform 1760 to 1750 Ma dates obtained over a widespread region (whether located near or far from post-tectonic plutons) argue against a simply contact related phenomenon.

It is interesting to note that in Minnesota the region of ~1760 Ma plutonism and amphibolite facies metamorphism is concentrated within the internal zone of the Penokean orogen. Metamorphic grade decreases rapidly within the medial zone north of the Malmo Structural Discontinuity where plutonism is absent. In addition, rocks located to the south in the Minnesota River Valley cooled to below ~300°C by 1840 to 1780 Ma (Goldich and others, 1961; this study), well before the rocks of the internal zone were remetamorphosed to amphibolite facies. Garnet rim pressures within the internal zone rocks are essentially no different from garnet core pressures suggesting these rocks underwent little to no uplift for 50 my after the orogeny. It appears however that at ~50 to 60 my after the cessation of the Penokean orogeny, the deepest exposed and probably thickest portion of the orogenic belt became unstable and rapidly collapsed. We believe that increased heat-flux at the base of the crust in the thickest portion of the orogenic belt (the internal zone) was responsible for both partial melting of the lower crust and regional metamorphism to staurolite grade of the middle crust. Although it is difficult to assess the cause of the increased heat-flux, the late mafic dikes of probable Early Proterozoic age attest to an important mantle contribution at that time (Horan, Hanson, and Spencer, 1987; Spencer, ms; Holm and Lux, 1996).

The metamorphism, intrusion, and rapid exhumation of the internal zone of the Penokean orogen was the last major "event" to have affected this region aside from the final formation of the McGrath Gneiss dome around 1700 Ma (Holm and Lux, 1996). In northern Wisconsin the ~1760 Ma magmatic event was followed by subsidence and deposition of the mature quartzites of the Baraboo interval (Dott, 1983; Greenberg and Brown, 1983). Medaris and others (1996) present conclusive evidence that the Baraboo Quartzite is depositional on the 1752 Ma Baxter Hollow granite, and Dott, Medaris, and Schott (1997) report Pb/Pb detrital zircon dates as young as 1712 Ma from the quartzite. In southwestern Minnesota, Chandler and Morey (1992) present paleomagnetic evidence that the correlatable Sioux Quartzite is also post-1750 Ma. These quartzites represent stabilization of continental crust in the Lake Superior region after a protracted history of tectonic instability which lasted hundreds of millions of years. It appears that the sudden and rapid collapse of the overthickened Penokean orogen together with thermal re-equilibration of the lithosphere was a critical step in crustal stabilization during the Early Proterozoic (Rogers and others, 1984; Nelson, 1991).

The extent and nature of ~1760 Ma metamorphism within the Penokean orogen in Wisconsin is just beginning to be unraveled (Van Wyck, ms; Romano and others, 1997). Van Wyck (ms) illustrated a thermal disturbance adjacent to an ~1760 Ma pluton in central Wisconsin, and Romano and others (1997) obtained evidence for partial thermal resetting interpreted to be related to ~1760 Ma magmatism in northwest Wisconsin. However, these disturbances appear to be a more localized contact-related phenomenon because several localities in Wisconsin and upper Michigan yield hornblende $^{40}Ar/^{39}Ar$ dates that reflect cooling from Penokean-age metamorphism (that is, 1800-1850 Ma; Schneider, Holm, and Lux, 1996; Romano and others, 1997; Mancuso, Holm, and Foland, 1997). This is also consistent with the fact that the ~1760 Ma granites in this part of the orogen were emplaced at somewhat shallower depths than similar age granites in central Minnesota (Anderson, Cullers, and Van Schmus, 1980). It appears then that the nature and extent of 1760 Ma metamorphism is distinctly different within different parts of the orogenic belt. We speculate that the differences may reflect initial differences in the amount of crustal thickening attained across the Early Proterozoic orogen. Post-orogenic metamorphism appears to have been more regional in nature in central Minnesota perhaps because Penokean metamorphism was deeper there than in the island arc terrane of Wisconsin (Geiger and Guidotti, 1989). Whatever the reason, recognition and characterization of post-orogenic metamorphism are essential for understanding cratonic evolution in the Proterozoic.

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APPENDIX A

Microprobe data used in calculating temperature and pressure for sample MN-29, reported as cations per 24, 22, and 8 oxygens for garnet, mica, and feldspar, respectively

Probe Point	Name	Wt. % Oxide	Si	Al	Ti	Mg	Fe^{2+} *	Mn	Ca	Na	K
1	1a grt rim	99.250	5.953	4.022	0.001	0.628	4.532	0.438	0.461	0.000	0.000
2	1b grt rim	99.829	5.988	3.985	0.014	0.468	4.141	0.593	0.813	0.000	0.000
3	1 bio	98.789	5.275	3.750	0.167	2.058	2.533	0.021	0.000	0.062	1.699
4	1 bio	98.994	5.378	3.617	0.170	2.105	2.477	0.013	0.001	0.071	1.696
5	1 bio	98.865	5.367	3.656	0.169	2.054	2.498	0.023	0.000	0.080	1.658
6	1c grt core	99.830	5.996	4.057	0.009	0.350	3.869	0.969	0.718	0.000	0.000
7	1d grt rim	100.875	5.960	4.036	0.005	0.543	4.350	0.553	0.569	0.000	0.000
8	1d bio	99.132	5.419	3.611	0.181	2.058	2.419	0.018	0.007	0.067	1.691
9	1e grt rim	100.242	5.956	4.044	0.004	0.617	4.429	0.606	0.362	0.000	0.000
10	1e feld	100.325	2.788	1.218	0.000	0.000	0.005	0.000	0.222	0.735	0.004
11	2a grt rim	99.444	6.008	4.045	0.004	0.543	4.276	0.801	0.287	0.000	0.000
13	2b grt rim	99.595	5.887	4.077	0.006	0.620	4.531	0.588	0.361	0.000	0.000
14	2b bio	98.981	5.337	3.631	0.168	2.129	2.528	0.004	0.000	0.080	1.681
15	2c grt core	99.727	5.957	4.049	0.007	0.364	3.904	0.944	0.784	0.000	0.000
17	2d feld	100.988	2.751	1.249	0.000	0.000	0.011	0.000	0.237	0.742	0.011
18	2d grt rim	99.103	6.010	4.050	0.009	0.601	4.300	0.672	0.314	0.000	0.000
19	2e grt im	99.692	6.001	4.040	0.003	0.621	4.365	0.478	0.468	0.000	0.000
20	musc	98.501	6.069	5.734	0.118	0.093	0.091	0.000	0.000	0.240	1.446
21	musc	99.187	6.087	5.801	0.038	0.072	0.093	0.000	0.000	0.265	1.506
22	3a grt rim	99.220	5.989	4.053	0.000	0.568	4.364	0.607	0.405	0.000	0.000
23	3a bio	100.661	5.325	3.627	0.181	2.151	2.505	0.026	0.003	0.079	1.646
24	3b grt rim	100.846	5.949	4.070	0.002	0.610	4.416	0.436	0.530	0.000	0.000
25	3b feld	101.518	2.760	1.241	0.000	0.000	0.005	0.000	0.231	0.758	0.006
27	3c grt	99.111	5.940	4.031	0.003	0.500	4.268	0.621	0.678	0.000	0.000
28	3d grt core	99.214	5.920	4.057	0.007	0.367	3.890	0.992	0.810	0.000	0.000
29	mat bio	100.424	5.394	3.549	0.195	1.077	3.532	0.015	0.000	0.098	1.650

* Total Fe reported as FeO.

Microprobe data used in calculating temperature and pressure for sample P-16 reported as cations per 24, 22, and 8 oxygens for garnet, mica, and feldspar, respectively

Probe Point	Name	Wt. % Oxide	Si	Al	Ti	Mg	Fe^{2+} *	Mn	Ca	Na	K
30	1a grt rim	99.442	5.949	4.080	0.000	0.701	4.782	0.083	0.405	0.000	0.000
33	1a bio	97.633	5.436	3.452	0.182	2.350	2.319	0.005	0.010	0.085	1.717
35	1b grt rim	99.596	5.944	4.071	0.000	0.712	4.772	0.071	0.450	0.000	0.000
36	1b bio	99.732	5.389	3.478	0.176	2.458	2.381	0.006	0.000	0.066	1.552
38	1c mus	100.223	6.073	5.772	0.035	0.081	0.100	0.000	0.005	0.512	1.367
39	1d grt rim	99.560	5.927	4.079	0.006	0.687	4.731	0.092	0.506	0.000	0.000
40	1d bio	100.495	5.398	3.502	0.172	2.374	2.345	0.005	0.005	0.084	1.670
42	1e grt core	100.011	5.925	4.063	0.010	0.330	3.744	0.789	1.171	0.000	0.000
43	1f feld	101.499	2.733	1.265	0.000	0.000	0.004	0.000	0.256	0.749	0.002
45	2b grt rim	100.160	5.925	4.075	0.002	0.688	4.743	0.075	0.527	0.000	0.000
44	2a feld	101.067	2.722	1.279	0.000	0.000	0.000	0.000	0.279	0.715	0.000
46	2b bio	99.951	5.419	3.434	0.189	2.470	2.293	0.010	0.000	0.087	1.635
49	2d musc	103.231	6.058	5.817	0.028	0.091	0.104	0.000	0.000	0.352	1.460
50	3d grt rim	100.005	6.001	4.064	0.002	0.695	4.714	0.076	0.414	0.000	0.000
51	3d bio	100.000	4.024	4.546	0.010	3.840	3.259	0.002	0.006	0.006	0.007
53	3e grt core	99.084	5.961	4.062	0.001	0.348	3.809	0.639	1.167	0.000	0.000
54	3f feld	101.806	2.749	1.253	0.000	0.000	0.003	0.000	0.247	0.745	0.002
56	mat b 2	99.684	5.345	3.540	0.161	2.417	2.445	0.006	0.000	0.065	1.558
57	mat b 3	99.462	5.364	3.498	0.185	2.387	2.381	0.002	0.000	0.079	1.694
58	2e grt core	99.330	5.960	4.043	0.013	0.324	3.761	0.722	1.180	0.000	0.000

* Total Fe reported as FeO.

APPENDIX B

$^{40}Ar/^{39}Ar$ analytical data of dated samples, central Minnesota

Temp., (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	^{39}Ar, moles*	^{39}Ar, % of Total	$^{40}Ar_{rad}$, %	K/Ca	AGE (Ma)
MN-38-Hornblende (J = 0.007875)								
770	174.00	0.145	0.0235	148.8	4.1	96.0	3.379	1514.8 ± 10.3
860	188.14	0.155	0.0131	224.5	6.1	97.9	3.153	1617.5 ± 12.0
945	195.63	0.255	0.0110	307.4	8.4	98.3	1.921	1664.1 ± 12.1
1020	203.13	2.012	0.0044	356.2	9.7	99.4	0.243	1718.7 ± 11.7
1080	204.84	2.856	0.0027	762.5	20.8	99.7	0.171	1731.9 ± 11.7
1145	206.20	2.765	0.0006	717.4	19.6	100.0	0.177	1742.4 ± 11.4
1200	205.69	3.031	0.0027	531.9	14.5	99.7	0.161	1736.6 ± 12.4
1260	205.88	3.207	0.0025	342.2	9.4	99.8	0.152	1738.2 ± 11.8
1310	206.77	3.211	0.0012	156.8	4.3	99.9	0.152	1745.1 ± 12.2
1360	206.34	3.270	0.0089	80.5	2.2	98.8	0.150	1730.4 ± 12.7
FUSE	205.45	3.311	0.0152	29.3	0.8	97.9	0.148	1715.4 ± 28.3
TOTAL				3657.6	100.0			1712.8 ± 11.9
PLATEAU AGE								1738.8 ± 19.0
PX-1A-Hornblende (J = 0.00882)								
770	203.99	0.915	0.2309	90.0	2.7	66.6	0.535	1421.3 ± 14.0
940	187.66	2.420	0.0942	144.0	4.3	85.3	0.202	1589.5 ± 14.0
1010	189.12	3.474	0.0388	227.5	6.7	94.1	0.141	1704.8 ± 11.4
1090	189.63	4.040	0.0134	485.6	14.4	98.1	0.121	1754.6 ± 12.1
1130	188.90	3.923	0.0060	719.8	21.4	99.2	0.125	1763.2 ± 14.0
1205	189.46	4.048	0.0055	1043.7	31.0	99.3	0.121	1767.6 ± 11.4
1255	191.25	4.165	0.0065	264.7	7.9	99.1	0.117	1776.6 ± 12.3
1310	193.54	4.588	0.0086	199.5	5.9	98.9	0.106	1787.1 ± 11.6
1365	195.23	4.570	0.0205	64.0	1.9	97.1	0.107	1776.2 ± 24.7
FUSE	197.94	4.943	0.0355	132.4	3.9	94.9	0.099	1766.4 ± 24.7
TOTAL				3371.2	100.0			1745.7 ± 13.1
PLATEAU AGE								1761.8 ± 22.0
MN-23-Hornblende (J = 0.0088245)								
770	200.22	0.773	0.1085	67.1	2.8	84.0	0.633	1642.2 ± 18.7
965	157.05	0.586	0.0595	118.3	4.9	88.8	0.836	1448.0 ± 14.5
940	125.42	1.218	0.0267	92.7	3.9	93.8	0.402	1285.0 ± 30.8
1010	142.59	2.519	0.0197	90.9	3.8	96.0	0.194	1431.1 ± 12.2
1090	175.19	4.617	0.0087	266.6	11.1	98.7	0.106	1675.2 ± 11.1
1130	184.40	4.848	0.0049	258.0	10.7	99.4	0.101	1739.6 ± 12.2
1205	185.03	4.415	0.0045	587.4	24.4	99.4	0.111	1743.6 ± 11.5
1255	185.24	4.237	0.0073	339.2	14.1	99.0	0.115	1739.7 ± 11.7
1310	185.67	4.124	0.0113	466.6	19.4	98.4	0.118	1735.0 ± 11.8
FUSE	185.02	3.794	0.0292	119.0	4.9	95.5	0.129	1698.0 ± 20.0
TOTAL				2405.8	100.0			1684.3 ± 13.2
PLATEAU AGE								1739.5 ± 15.8
K-4B-Hornblende (J = 0.008958)								
770	199.03	2.370	0.1196	70.2	3.0	82.3	0.206	1631.4 ± 13.5
860	152.48	0.392	0.0537	89.7	3.8	89.6	1.249	1442.2 ± 11.7
945	137.97	1.048	0.0445	81.7	3.5	90.5	0.467	1355.2 ± 21.7
1020	150.38	3.067	0.0192	103.7	4.4	96.4	0.159	1503.3 ± 12.3
1080	169.26	4.929	0.0087	198.2	8.5	98.7	0.099	1654.1 ± 11.8
1145	175.23	5.940	0.0050	437.6	18.7	99.4	0.082	1700.6 ± 12.1
1200	175.15	5.962	0.0055	444.1	19.0	99.3	0.082	1699.1 ± 12.0
1260	174.50	3.723	0.0038	361.7	15.5	99.5	0.131	1695.5 ± 12.1
1310	172.76	4.885	0.0103	245.2	10.5	98.4	0.100	1673.5 ± 12.9
1360	174.38	4.738	0.0137	205.0	8.8	97.9	0.103	1677.4 ± 11.5
FUSE	178.67	9.141	0.0331	101.9	4.4	94.9	0.053	1673.5 ± 13.3
TOTAL				2339.0	100.0			1656.7 ± 25.5
PLATEAU AGE								1698.4 ± 13.6
MN-31-Biotite (J = 0.007841)								
770	176.52	0.269	0.0752	76.9	3.4	87.4	1.8	1430.6 ± 23.4
915	206.27	0.004	0.0007	325.7	14.2	99.9	109.0	1734.6 ± 11.4
1020	207.77	0.037	0.0020	416.6	18.2	99.7	13.1	1740.6 ± 11.6
1080	207.65	0.013	0.0007	456.3	19.9	99.9	36.7	1742.1 ± 12.2
1145	207.67	0.042	0.0026	418.5	18.3	99.6	11.8	1739.2 ± 11.8
1225	208.24	0.067	0.0011	336.7	14.7	99.8	7.3	1744.7 ± 11.5
1310	205.16	0.188	0.0035	173.9	7.6	99.5	2.6	1724.3 ± 13.6
FUSE	205.75	0.129	0.0078	87.8	3.8	98.9	3.8	1720.6 ± 12.9
TOTAL				2292.4	100.0			1728.0 ± 27.9
PLATEAU AGE								1741.7 ± 13.4

APPENDIX B (*continued*)

$^{40}Ar/^{39}Ar$ analytical data of dated samples, central Minnesota

Temp., (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	^{39}Ar, moles*	^{39}Ar, % of Total	$^{40}Ar_{rad}$, %	K/Ca	AGE (Ma)
P-11A-Hornblende (J = 0.008979)								
770	784.95	36.06	2.0006	3.7	0.1	25.0	0.013	1863.2 ± 636.0
860	405.45	2.119	0.8984	6.7	0.3	34.6	0.231	1470.8 ± 170.5
945	272.81	31.68	0.4912	5.5	0.2	47.7	0.015	1416.9 ± 141.1
1020	201.08	9.547	0.1430	12.2	0.5	79.3	0.051	1610.6 ± 67.6
1080	185.31	4.173	0.0117	84.2	3.4	98.3	0.117	1751.4 ± 14.1
1145	181.74	5.193	0.0043	453.8	18.5	99.5	0.094	1744.2 ± 11.3
1200	181.88	5.096	0.0037	749.1	30.5	99.6	0.096	1745.9 ± 11.3
1260	182.45	5.386	0.0037	485.6	19.8	99.6	0.091	1749.8 ± 11.6
1310	182.96	5.421	0.0036	297.7	12.1	99.6	0.090	1753.4 ± 11.8
1360	183.76	5.582	0.0076	235.5	9.6	99.0	0.087	1751.2 ± 11.5
FUSE	187.32	3.954	0.0164	120.2	4.9	97.6	0.124	1754.9 ± 15.4
TOTAL				2454.0	100.0			1746.4 ± 13.7
PLATEAU AGE								1749.3 ± 15.7
MN-38-Biotite (J = 0.007455)								
1080	218.01	0.041	0.0025	211.1	30.1	99.7	11.9	1737.5 ± 11.4
1145	217.42	0.042	0.0038	151.9	21.7	99.5	11.6	1732.4 ± 11.3
1235	220.88	0.157	0.0025	200.1	28.5	99.7	3.1	1752.2 ± 13.5
1310	217.99	0.167	0.0020	97.0	13.8	99.7	2.9	1738.2 ± 12.8
FUSE	212.62	0.206	0.0060	41.5	5.9	99.2	2.4	1704.2 ± 24.2
TOTAL				701.5	100.0			1738.7 ± 12.9
MN-R-Biotite (J = 0.007588)								
770	186.86	0.441	0.0143	153.1	5.2	97.7	1.1	1569.1 ± 11.1
915	202.39	0.101	0.0022	358.7	12.1	99.7	4.9	1675.1 ± 11.4
1020	204.55	0.126	0.0036	405.0	13.7	99.5	3.9	1684.6 ± 11.3
1080	204.89	0.121	0.0020	392.8	13.2	99.7	4.0	1689.0 ± 11.3
1145	205.58	0.185	0.0014	525.8	17.7	99.8	2.6	1693.7 ± 11.5
1235	206.15	0.118	0.0013	568.5	19.2	99.8	4.2	1696.9 ± 11.5
1310	206.57	0.214	0.0006	366.0	12.3	99.9	2.3	1700.2 ± 11.1
FUSE	208.35	0.504	0.0086	195.2	6.6	98.8	1.0	1697.5 ± 13.3
TOTAL				2965.2	100.0			1684.8 ± 11.5
PLATEAU AGE								1697.1 ± 13.5
MN-34-Biotite (J = 0.007572)								
770	219.54	0.442	0.1718	48.2	1.9	76.9	1.1	1485.7 ± 16.9
915	215.62	0.046	0.0181	314.8	12.3	97.5	10.6	1718.3 ± 12.2
1020	216.43	0.063	0.0068	385.5	15.0	99.1	7.8	1740.1 ± 11.7
1080	215.09	0.031	0.0047	414.8	16.2	99.3	15.8	1736.3 ± 11.5
1145	216.45	0.040	0.0025	351.4	13.7	99.7	12.3	1746.7 ± 11.4
1235	216.46	0.050	0.0017	490.4	19.1	99.8	9.7	1748.0 ± 11.4
1310	217.89	0.073	0.0021	394.1	15.4	99.7	6.8	1754.9 ± 11.5
FUSE	218.65	0.298	0.0105	166.5	6.5	98.6	1.6	1746.2 ± 13.4
TOTAL				2565.7	100.0			1737.1 ± 11.8
PLATEAU AGE								1749.0 ± 17.0
S-2-Biotite (J = 0.007532)								
770	168.37	0.039	0.0178	139.7	5.5	96.9	12.4	1445.7 ± 12.0
915	204.70	0.012	0.0050	279.4	11.0	99.3	40.9	1675.0 ± 13.0
1020	213.41	0.060	0.0063	285.5	11.2	99.1	8.2	1719.2 ± 12.0
1080	216.40	0.023	0.0024	278.2	10.9	99.7	21.4	1740.8 ± 12.1
1145	217.92	0.038	0.0003	336.7	13.2	100.0	13.1	1751.8 ± 11.5
1235	218.39	0.020	0.0017	505.1	19.8	99.8	23.9	1752.0 ± 11.8
1310	218.89	0.036	0.0042	444.1	17.4	99.4	13.4	1750.9 ± 11.5
FUSE	220.12	0.007	0.0086	280.6	11.0	98.8	67.0	1750.5 ± 12.3
TOTAL				2549.2	100.0			1721.5 ± 24.0
PLATEAU AGE								1751.3 ± 10.5
MRV-1-Biotite (J = 0.007884)								
770	231.37	0.230	0.3631	37.2	2.6	53.6	2.1	1230.8 ± 83.3
915	214.02	0.010	0.0367	165.3	11.7	94.9	48.4	1725.0 ± 12.0
1020	214.62	0.015	0.0180	334.3	23.6	97.5	33.8	1758.2 ± 11.8
1080	215.37	0.058	0.0024	222.7	15.7	99.7	8.4	1786.8 ± 16.3
1145	213.21	0.035	0.0000	263.5	18.6	100.0	14.1	1779.0 ± 11.9
1235	214.97	0.032	0.0017	227.5	16.0	99.8	15.5	1785.7 ± 16.9
1310	212.09	0.029	0.0027	116.5	8.2	99.6	17.0	1768.9 ± 18.9
FUSE	204.71	0.119	0.0017	51.9	3.7	99.7	4.1	1730.8 ± 36.3
TOTAL				1418.9	100.0			1753.2 ± 16.7
PLATEAU AGE								1783.9 ± 17.4

* $\times 10^{-14}$.

References

Ague, J. J., and Brimhall, G. H., 1988, Magmatic arc asymmetry and distribution of anomalous plutonic belts in the batholiths of California: Effects of assimilation, crustal thickness, and depth of crystallization: Geological Society of America Bulletin, v. 100, p. 912–927.
Anderson, J. L., Cullers, R. L., and Van Schmus, W. R., 1980, Anorogenic metaluminous and peraluminous granite plutonism in the Mid-Proterozoic of Wisconsin, USA: Contributions to Mineralogy and Petrology, v. 74, p. 311–328.
Beakhouse, G. P., McNutt, R. H., and Krogh, T. E., 1988, Comparative Rb-Sr and U-Pb zircon geochronology of late- to post-tectonic plutons in the Winnipeg River Belt, northwestern Ontario, Canada: Chemical Geology, v. 72, p. 337–351.
Chandler, V. W., and Morey, G. B., 1992, Paleomagnetism of the Early Proterozoic Sioux Quartzite, southwestern Minnesota–Implications for Correlating Quartzites of the Baraboo Interval, *in* Sims, P. K., and Carter, L. M. H., editors, Contributions to Precambrian Geology of Lake Superior Region: United States Geological Survey Bulletin 1904-N. p. N1–N14.
Dacre, G. S., Himmelberg, G. R., and Morey, G. B., 1984, Pre-Penokean igneous and metamorphic rocks, Benton and Stearns counties, central Minnesota: Minnesota Geological Survey Report of Investigations 31, 16 p.
Darrah, K. S., ms, 1996, An exhumation history of the internal zone of the Early Proterozoic (1870-1820 Ma) Penokean orogenic belt, central Minnesota: M.S. thesis, Kent State University, 101 p.
Dott, R. H., Jr., 1983, The Proterozoic red quartzite enigma in the north-central U.S.–resolved by plate collision?: Geological Society of America Memoir 160, p. 129–141.
Dott, R. H., Jr., Medaris, L. G., Jr., and Schott, R. C., 1997, Post-1760 Ma deposition of the Baraboo quartzite: Confirmation from detrital zircon ages and new field evidence: Geological Society of America Abstracts with Programs, v. 29, p. 13.
Ferry, J. M., and Spear, F. S., 1978, Experimental calibration of the partitioning of Fe and Mg between biotite and garnet: Contributions to Mineralogy and Petrology, v. 66, p. 113–117.
Geiger, C. A., and Guidotti, C. V., 1989, Precambrian metamorphism in the southern Lake Superior region and its bearing on crustal evolution: Geoscience Wisconsin, v. 13, p. 1–33.
Ghent, E. D., and Stout, M. Z., 1981, Geobarometry and geothermometry of plagioclase-biotite-garnet-muscovite assemblages: Contributions to Mineralogy and Petrology, v. 76, p. 92–97.
Goldich, S. S., and Fischer, L. B., 1986, Air abrasion experiments in U-Pb dating of zircon: Chemical Geology, v. 58, p. 195–215.
Goldich, S. S., Hedge, C. E., and Stern, T. V., 1970, Age of the Morton and Montevidieo Gneisses and related rocks, Southwestern Minnesota: Geological Society of America Bulletin, v. 81, p. 3671–3696.
Goldich, S. S., Nier, A. O., Baadsgaard, H., Hoffman, J. H., and Krueger, H. W., 1961, The Precambrian geology and geochronology of Minnesota: Minnesota Geological Survey Bulletin 41, 193 p.
Green, J. C., Bornhorst, T. J., Chandler, V. W., Mudrey, M. G., Myers, P. E., Pesonen, L. J., and Wilband, J. T., 1987, Keweenawan dykes of the Lake Superior region: Evidence for Evolution of the Middle Proterozoic midcontinent rift of North America, *in* Hall, H. C., and Fahrig, W. F., editors, Mafic dyke swarms: Geological Association of Canada Special Paper 34, p. 289–302.
Greenberg, J. K., and Brown, B. A., 1983, Cratonic sedimentation during the Proterozoic: An anorogenic connection in Wisconsin and the upper midwest: Journal of Geology, v. 92, p. 159–171.
——— 1985, Deformational and metamorphic features associated with 1500 Ma anorogenic magmatism in Wisconsin, *in* The crust–the significance of granite and gneisses in the lithosphere: Athens. Theophrastus Publications, p. 79–93.
Hammarstrom, J. M., and Zen, E-an, 1986, Aluminum in hornblende: An empirical igneous geobarometer: American Mineralogist, v. 71, p. 1297–1313.
Hanson, G. N., 1968, K-Ar ages for hornblende from granites and gneisses and for basaltic intrusives in Minnesota: Minnesota Geological Survey Report of Investigations 8, 20 p.
Hanson, G. N., and Himmelberg, G. R., 1967, Ages of mafic dikes near Granite Falls, Minnesota: Geological Society of America Bulletin, v. 78, p. 1429–1432.
Hemming, S. R., McLennan, S. M., and Hanson, G. N., 1995, Geochemical and Nd/Pb isotopic evidence for the Provenance of the Early Proterozoic Virginia Formation, Minnesota. Implications for the tectonic setting of the Animikie Basin: Journal of Geology, v. 103, p. 147–168.
Hodges, K. V., and Crowley, P. D., 1985, Error estimations and empirical geothermobarometry for pelitic systems: American Mineralogist, v. 70, p. 702–709.
Hodges, K. V., and Spear, F. 1982, Geothermometry, geobarometry and the Al_2SiO_5 triple point at Mt. Moosilauke, New Hampshire: American Mineralogist, v. 67, p. 1118–1134.
Hoffman, P. F., 1988, United Plates of America, the birth of a craton; Early Proterozoic assembly and growth of Laurentia: Annual Reviews of Earth and Planetary Sciences, v. 16, p. 543–603.
Hollister, L. S., Grissom, G. C., Peters, E. K., Stowell, H. H., and Sisson, V. B., 1987, Confirmation of the empirical correlation of Al in hornblende with pressure of solidification of calc-alkaline plutons: American Mineralogist, v. 72, p. 231–239.
Holm, D. K., Holst, T. B., and Ellis, M. A., 1988, Oblique subduction, footwall deformation, and imbrication: a model for the Penokean orogeny, Minnesota: Geological Society of America Bulletin, v. 100, p. 1811–1818.
Holm, D. K., Holst, T. B., and Lux, D. R., 1993, Postcollisional cooling of the Penokean orogen in east-central Minnesota: Canadian Journal of Earth Sciences, v. 30, p. 913–917.
Holm, D. K., and Lux, D. R., 1996, Core complex model proposed for gneiss dome development during collapse of the Paleoproterozoic Penokean orogen, Minnesota: Geology, v. 24, p. 343–346.
——— 1997, Results of Ar/Ar dating of dikes in central Minnesota and the Minnesota River Valley: Annual Meeting of the Institute on Lake Superior Geology, Sudbury, Ontario, v. 43, p. 23–24.

Holm, D. K., and Selverstone, J., 1990, Rapid growth and strain rates inferred from synkinematic garnets, Penokean orogeny, Minnesota: Geology, v. 18, p. 166–169.

Holst, T. B., 1984, Evidence for nappe development during the Early Proterozoic Penokean orogeny, Minnesota: Geology, v. 12, p. 135–138.

Horan, M. F., Hanson, G. N., and Spencer, K. J., 1987, Pb and Nd isotope and trace element constraints on the origin of basic rocks in an Early Proterozoic igneous complex, Minnesota: Precambrian Research, v. 37, p. 323–342.

Johnson, M. C., and Rutherford, M. J., 1989, Experimental calibration of the aluminum in hornblende geobaromenter with application to Long Valley cauldera (California) volcanic rocks: Geology, v. 17, p. 837–841.

Keighin, C. W., Morey, G. B., and Goldich, S. S., 1972, East-central Minnesota, in Sims, P. K., and Morey, G. B., editors, Geology of Minnesota–A centennial volume: Minnesota Geological Survey, p. 240–255.

King, E. R., 1990, Precambrian terrane of north-central Wisconsin: an aeromagnetic perspective: Canadian Journal of Earth Sciences, v. 27, p. 1472–1477.

Labotka, T. C., Papike, J. J., and Morey, G. B., 1981, The effect of pressure on isochemical metamorphism of pelitic rocks from north central Minnesota: Geological Society of America Abstracts with Programs, v. 13, p. 493.

Lanzirotti, A., and Hanson, G. N., 1993, U-Pb dating of staurolite: Geological Society of America Abstracts with Programs, v. 25, p. A-35.

Lux, D. R., 1986, $^{40}Ar/^{39}Ar$ ages for minerals from the amphibolite dynamothermal aureole, Mont Albert, Gaspe, Quebec: Canadian Journal of Earth Sciences, v. 23, p. 21–26.

Mancuso, C., Holm, D. K., and Foland, K. A., 1997, Initial results of Ar/Ar mineral dating from northeastern Wisconsin: Annual Meeting of the Institute on Lake Superior Geology, Sudbury, Ontario, v. 43, p. 37–38.

McDougall, I., and Harrison, T. M., 1989, Geochronology and Thermochonology by the $^{40}Ar/^{39}Ar$ Method: New York, Oxford University Press, 212 pp.

Medaris, L. G., Jr., Johnson, C. M., Schott, R. C., Dott, R. H., and Van Wyck, N., 1996, The Baraboo Quartzite, Wisconsin: Proterozoic deposition and deformation in the Lake Superior region: Geological Society of America Abstracts with Programs, v. 28, p. A-376.

Morey, G. B., 1979, Field trip guidebook for the Precambrian geology of east-central Minnesota: Minnesota Geological Survey, Guidebook Series 12, 28 p.

——— , 1983, Lower Proterozoic stratified rocks and the Penokean orogeny in east-central Minnesota: Geological Society of America Memoir 160, p. 97–112.

Nelson, B. K., 1991, Proterozoic continental growth near the Archean craton: The isotopic record from anorogenic granites in Wisconsin: EOS (Transactions of American Geophysical Union), v. 72, p. 544.

Nelson, K. D., 1991, A unified view of craton evolution motivated by recent deep seismic reflection and refraction studies: Geophysical Journal International, v. 105, p. 25–35.

Peterman, Z. E., and Sims, P. K., 1988, The Goodman Swell: A lithospheric flexure caused by crustal loading along the midcontinent rift system: Tectonics, v. 7, p. 1077–1090.

Peterman, Z. E., Sims, P. K., Zartman, R. E., and Schulz, K. J., 1985, Middle Proterozoic uplift events in the Dunbar dome of northeastern Wisconsin, USA: Contributions to Mineralogy and Petrology, v. 91, p. 138–150.

Rogers, J. J. W., Dabbagh, M. E., Olszewski, W. J., Gaudette, H. E., Greenberg, J. K., and Brown, B. A., 1984, Early poststabilization sedimentation and later growth of shields: Geology, v. 12, p. 607–609.

Romano, D., Holm, D. K., Foland, K. A., and Hubacher, F. A., 1997, Metamorphism and cooling of Precambrian rocks in northwest Wisconsin: Initial results of Ar/Ar dating: Geological Society of America Abstracts with Programs, v. 29, p. 69.

Schneider, D., Holm, D., and Lux, D., 1996, On the origin of Early Proterozoic gneiss domes and metamorphic nodes, northern Michigan: Canadian Journal of Earth Sciences, v. 33, p. 1053–1063.

Schmidt, M. W., 1992, Amphibole composition in tonalite as a function of pressure: an experimental calibration of the Al-in-hornblende barometer: Contributions to Mineralogy and Petrology, v. 110, p. 304–310.

Sims, P. K., Card, K. D., Morey, G. B., and Peterman, Z. E., 1980, The Great Lakes tectonic zone–A major crustal structure in central North America: Geological Society of America Bulletin, part 1, v. 91, p. 690–698.

Sims, P. K., and Day, W. C., 1993, The Great Lakes Tectonic Zone–Revisited, *in* Sims, P. K., and Carter, L. M. H., editors, Contributions to Precambrian Geology of Lake Superior Region: United States Geological Survey Bulletin 1904-S, p. S1–S11.

Sims, P. K., Van Schmus, W. R., Schulz, K. J., and Peterman, Z. E., 1989, Tectono-stratigraphic evolution of the Early Proterozoic Wisconsin magmatic terranes of the Penokean orogen: Canadian Journal of Earth Sciences, v. 26, p. 2145–2158.

Simpson, C., 1985, Deformation of granitic rocks across the brittle-ductile transition: Journal of Structural Geology, v. 7, p. 503–511.

Southwick, D. L., and Chandler, V. W., 1996, Block and shear-zone architecture of the Minnesota River Valley subprovince: implications for late Archean accretionary tectonics: Canadian Journal of Earth Sciences, v. 33, p. 831–847.

Southwick, D. L., and Morey, G. B., 1991, Tectonic imbrication and foredeep development in the Penokean orogen, east-central Minnesota–an interpretation based on regional geophysics and the results of test-drilling, *in* Sims, P. K., and Carter, L. M. H., editors, Contributions to Precambrian geology of Lake Superior region: U.S. Geological Survey Bulletin 1904, p. C1–C17.

Southwick, D. L., Morey, G. B., and McSwiggen, P. L., 1988, Geologic map of the Penokean orogen, central and eastern Minnesota, and accompanying text: Minnesota Geological Survey Report of Investigations 37, scale 1:250,000.

Spencer, K. J., ms, 1987, Isotopic, major and trace element constraints on the sources of granites in an 1800 Ma igneous complex near St. Cloud, Minnesota: Ph.D. thesis, State University of New York at Stony Brook, 249 pp.

Spencer, K. J., and Hanson, G. N., 1984, Pb, Nd isotope and REE constraints on east-central Minnesota Proterozoic granites–Evidence for newly derived crustal components: EOS (Transactions of American Geophysical Union), v. 65, p. 292.

Van Schmus, W. R., 1976, Early and Middle Proterozoic history of the Great Lakes area, North America: Royal Society of London Philosophical Transactions, v. 280, p. 605–628.

——— 1980, Chronology of igneous rocks associated with the Penokean orogeny in Wisconsin, *in* Morey, G. B., and Hanson, G. N., editors, Selected studies of Archean gneisses and lower Proterozoic rocks, southern Canadian Shield: Geological Society of America Special Paper 182, p. 159–168.

Van Schmus, W. R., Medaris, L. G., and Banks, P. O., 1975, Geology and age of the Wolf River Batholith, Wisconsin: Geological Society of America Bulletin, v. 86, p. 907–914.

Van Schmus, W. R., Thurman, E. M., and Peterman, Z. E., 1975, Geology and Rb-Sr chronology of Middle Proterozoic rocks in eastern and central Wisconsin: Geological Society of America Bulletin, v. 86, p. 1255–1265.

Van Wyck, N., ms, 1995, Major and Trace element, Common Pb, Sm-Nd, and zircon geochronology constraints on petrogenesis and tectonic setting of pre- and Early Proterozoic rocks in Wisconsin: Ph.D. thesis, University of Wisconsin-Madison, p. 47–280.